Radiation Coupled Front Tracking Simulations for Laser Driven Shock Experiments

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Abstract

The purpose of this paper is to develop a numerical algorithm to track the preheat interface motion driven by radiation transfer in high-intensity laser experiments. Our front tracking algorithm is coupled to a radiation process through an inter-package coupling by connecting the output from a radhydro code HYADES to the input of FronTier code of front tracking. Our coupled algorithm is validated by comparing simulation results from both codes in both low and high radiation cases. Significant interface motion and deformation of the harmonic perturbation due to radiation preheat are observed in high radiation heat case.

Key words: Front tracking, Radiation coupling, Preheat motion

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1 Introduction

Recently, laboratory astrophysics has been playing an important role in studying astrophysical systems, especially in the case of supernova explosions. Modern high-intensity lasers produce energy densities in submillimeter-scale volumes large enough to access phenomena that otherwise appear only in energetic astrophysical systems. The aim of laser astrophysics experiments is to probe astrophysical dynamics directly by creating scaled reproductions of the astrophysical systems in the laboratory.

The first spherically diverging, hydrodynamically unstable laboratory experiments of relevance to supernovae (SNe) were reported in [1]. The experiments use laser radiation to explode a hemispherical capsule, having a perturbed outer surface, which is embedded within a volume of low-density foam. These experiments and simulations provide a well-scaled test of computer models of supernova explosion hydrodynamics. However, there is an important issue in these laser-driven experiments. The important question is the impact of the radiation preheat on the structure at the interface by the time the shock reaches it. Once the interface is heated, the material there will begin to move. One dimensional calculations find a level of radiation preheat that causes the interface to move about 2 μm to 50 μm by the time the shock reaches it, depending upon the target properties. This motion will alter the initial conditions for the experiment of interest, including the shape of the perturbed interface when the shock reaches it. If there is significant motion of the interface due to preheat, the profile of the surface will change during this motion. We believe the ripple amplitude will decrease, and will become non-sinusoidal through the introduction of harmonic components. As a result, we will only be able to specify the pre-hydro shock initial conditions to some degree of accuracy with current numerical methods.

In order to solve the problem, we need to track the pre-shock interface motion driven by radiation preheat. The purpose of this paper is to develop a radiation coupled front tracking algorithm to track the preheat motion of the interface. Front tracking as implemented in the code *FronTier* includes the ability to handle multidimensional wave interactions in both two [7,9,10] and three [6,5] space dimensions and is based on a composite algorithm that combines shock capturing on a spatial grid with a specialized treatment of the flow near the tracked fronts. Here we develop a radiation front tracking coupling algorithm to connect radiation output from HYADES [12] to FronTier input. The algorithm is designed to handle the following two cases. If radiation output data is taken when radiation effect is negligible, the data will be interpolated onto a front tracking grid as the initial data for the simulation. On the other hand, if the radiation process is important, the radiation code will provide the heat rate data in addition to the state data. The front tracking code will incorporate the radiation heat data into its energy equation as a source term. We have simulated two preheat laser experiments in low and high radiation heating. For the high radiation case, we have conducted simulations of both one and two dimensional preheat motions. We have observed significant interface motion leading to a reduction of the interface perturbation amplitude before the shock reaches the interface. Validation has been carried out by comparing the outputs of FronTier and HYADES.

2 Radiation Coupled Front Tracking Algorithm

Front tracking is a numerical method in which selected waves are explicitly represented in a discrete form of the solution. Examples include shock waves, contact discontinuities, and material interfaces. Other waves which may be tracked, such as leading and trailing edges of rarefaction waves, have continuous states but jumps in their first derivatives. Tracked waves are propagated using the appropriate equations of motion for the given model. For example, if the system of equations consists of a set of hyperbolic conservation laws, $\mathbf{u}_t + \nabla \bullet \mathbf{f} = \mathbf{h}$, then the instantaneous velocity s of a discontinuity surface satisfies the Rankine-Hugoniot equations, $s\,[\mathbf{u}] = [\mathbf{f}] \bullet \mathbf{n}$. Here $\mathbf{n}$ is the unit normal to the discontinuity surface. During a time step propagation, the type of a wave, and the flow field in a neighborhood of the wave determine a local time integrated velocity for each point on the wave in the direction normal to the wave front. Wave propagation consists of moving each point a distance $s\Delta t$ in the normal direction as well as computing the time updated states at the new position. Tracking preserves the mathematical structure of the discontinuous waves by maintaining the discrete jump at the wave front, thus eliminating numerical diffusion across the front. It also allows for the direct inclusion of the appropriate flow equations for the wave front in the numerical solution. For a detailed description of the front tracking algorithm, we refer to Glimm, Grove and Zhang [8]. The validation in spherical geometry was carried out by comparison with experiment, see Drake et al. [1] where supernova experiments and simulations were reported. For other validation studies in planar geometry, we refer to [11,4].

Front tracking is a fast algorithm in the sense that it can reduces the level of mesh refinement needed to achieve a specified error tolerance by a significant factor compared to corresponding methods without tracking, thus substantially reducing the computational time as well as memory usage for simulations with contacts or material interfaces. In [2,3], we reported a detailed, quantitative comparison of errors in spherical shock refraction simulations by tracked and untracked methods from the solution of the 2d axisymmetric Euler system. The comparison study was carried out for an unperturbed interface since this case admits an easily understood exact solution which can be obtained by

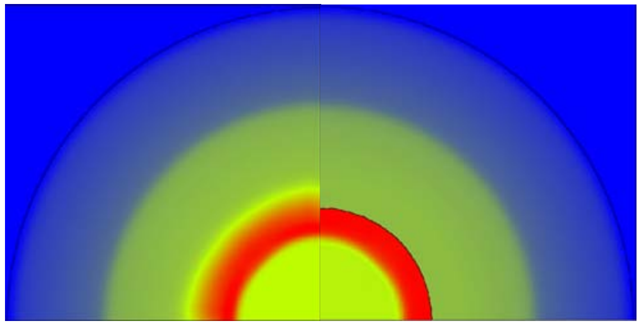

Fig. 1. *Density plots for a spherical implosion simulation with an unperturbed interface. The left image shows a contact shocked by implosion shock wave in the untracked case. The right image shows the tracked case at the same time. The grid size is* 100×100.

solving a 1d system of spherical Euler equations on a very fine mesh. The density plots for the spherical simulations with and without tracking are shown in Fig. 1, where we see the untracked interface was highly smeared by numerical diffusion. The main results in [2,3] can be summarized as follows. The error in the neighborhood of the untracked contact is the main contribution to the total error. Tracking the contact can effectively reduce both the contact error and the total error by a significant factor. For a given error tolerance, the mesh size needed to achieve a fixed error tolerance can be reduced by as much as a factor of eight per spatial dimension. A factor of $8^4 = 4096$ fewer space time zones for a three space dimensional computation are then required for comparable accuracy.

The simulations in this paper are based on numerical solutions to the Euler equations that describe the conservation of mass, momentum, and energy for a compressible fluid:

$$\rho_t + \nabla \cdot (\rho \mathbf{v}) + \alpha \frac{\rho u}{r} = 0, \tag{1}$$

$$(\rho \mathbf{v})_t + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla P + \alpha \frac{\rho u \mathbf{v}}{r} = \rho \mathbf{g}, \tag{2}$$

$$(\rho E)_t + \nabla \cdot \rho \mathbf{v}(E + P/\rho) + \alpha \frac{\rho u (E + P/\rho)}{r} = \rho \mathbf{v} \cdot \mathbf{g} + Q, \tag{3}$$

where ρ is the mass density, $\mathbf{v}$ the fluid velocity, P the thermodynamic pressure, $E = e + \frac{1}{2}\mathbf{v} \cdot \mathbf{v}$ the specific total energy, and e the specific internal energy. The variables ρ, P, and e are related by a thermodynamic equation of state $P = P(\rho, e)$. For simplicity we assume a perfect gas equation of state $P = (\gamma - 1)\rho e$, with $\gamma > 1$. The simulations reported in this paper use the value $\gamma = 5/3$. The body force per unit mass, $\mathbf{g}$, is taken as zero for the present discussion. The geometry parameter α has the value zero for rectangular geometries. For axisymmetric flow $\alpha = 1$, while $\alpha = 2$ for one dimensional spherical symmetry. For spherical symmetry u is the radial component of velocity and r is the distance from a point to the origin. For axi-symmetry u is the radial component of the projection of the fluid velocity into the $x-y$ plane and r is the distance of a point from the z axis. Here Q is the radiation heat rate per unit volume.

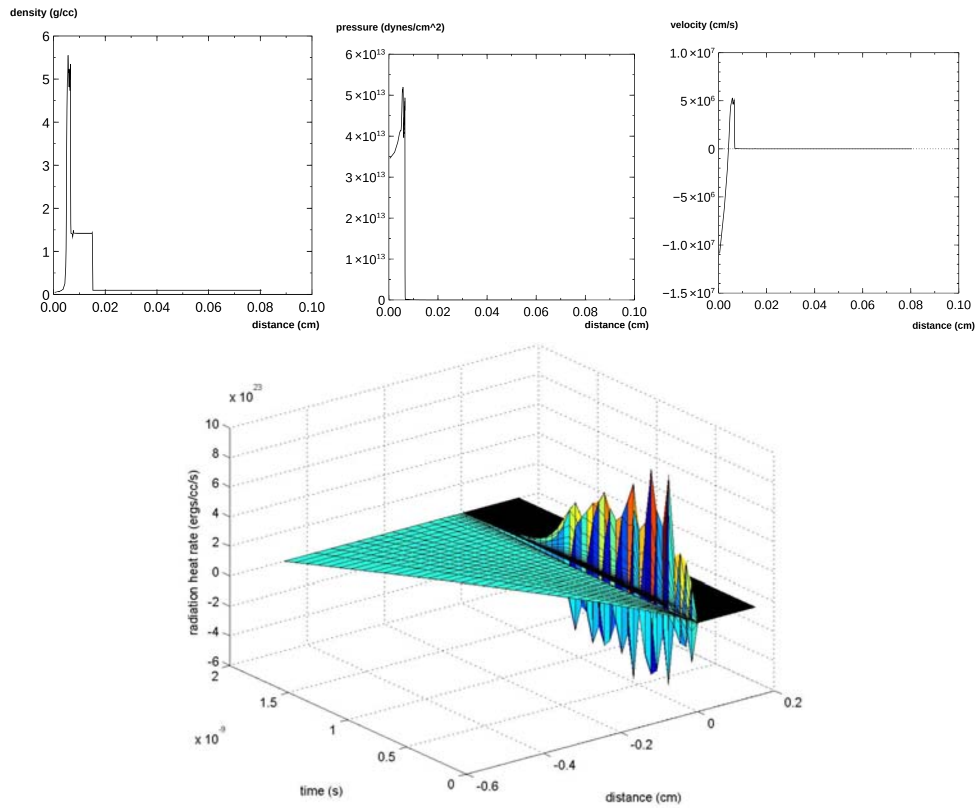

Fig. 2. *The images in the first row are the HYADES output at 1 ns as initial condition for FronTier for the low radiation case. The image in the second row is the space-time dependent radiation heat rate from HYADES as energy source for FronTier.*

For coupling the radiation process to FronTier code, we propose a pipeline method. A pipe denotes connection of the output of one code to the input of another. Coupling between two different packages can be challenging. Different codes use different grid systems. The codes can use Cartesian or curvilinear coordinates and they may use with Eulerian or Lagrangian variables. Adaptive mesh is another option. Therefore state communication between two software packages is a nontrivial task and requires an efficient and accurate interpolation algorithm to insure the smooth transition of data. The research team at University of Michigan prepared initial conditions from a one dimensional radiation-hydrodynamic code HYADES which is applied in 1D slices and used in our front tracking simulation. The algorithm for including a radiation heat source in FronTier has been developed for both one and two dimensional cases. The idea is that the output data from the radhydro code is taken as front tracking input before the interface starts to move due to radiation preheat. However, the radiation heat rate data are needed from this time until

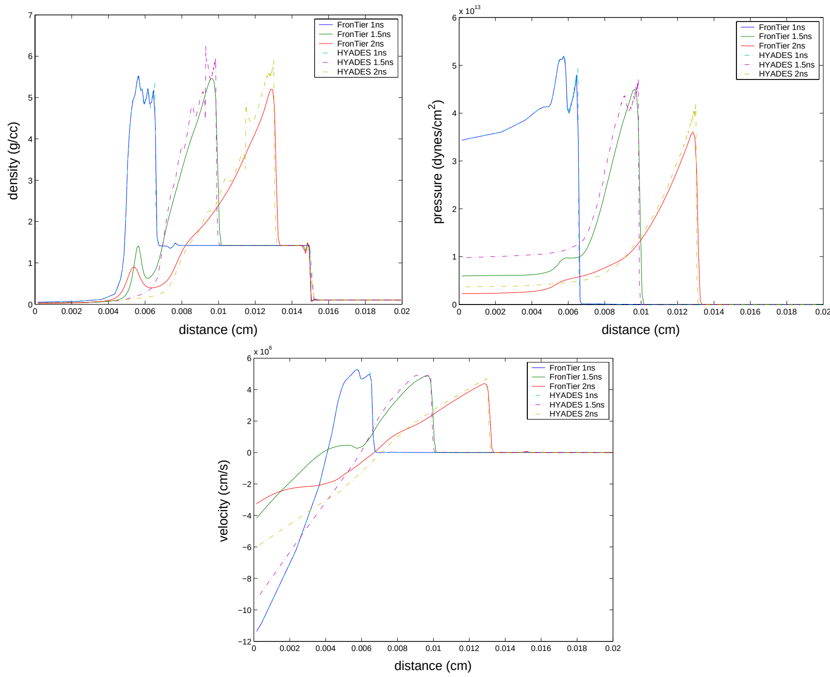

Fig. 3. *Comparison of FronTier and HYADES at 1 ns , 1.5 ns, and 2 ns for the low radiation case.*

the time when the radiation effect diminishes. We use this information to set up a time-and-space dependent energy source Q for the front tracking.

3 Low Radiation Heat

The target used in these simulations, and in experiments, has a 75 μm thick layer of polymide (at $\rho = 1.41\ g/cm^3$), followed by a 75 μm thick layer of brominated plastic (4.3% atomic Br, $\rho = 1.42\ g/cm^3$), followed in turn by a low-density ($\rho = 0.1 g/cm^3$) carbon foam. These experiments and simulations are done in planar geometry, intended to be a scaled representation of a small segment of an exploding star [13]. A strong shock is generated by Omega laser incident on the plastic. The HYADES [12] code is used for radiation transfer in the laser deposition experiments and to set up initial conditions and the radiation heat rate for FronTier input. HYADES as used here is a one-dimensional, Lagrangian, radiation-hydrodynamics code with multigroup diffusion radiation transport based on average-atom opacities, tabular equation of state using SESAME tables, and flux-limited diffusive electron heat transport. HYADES is believed to accurately calculate the radiation preheat produced by the interaction of the laser beam and the hot plasma it produces.

The output of HYADES at 1 ns was shown in Fig. 2 together with the space-time heat rate up to 2 ns, which will be used as energy source for FronTier. The

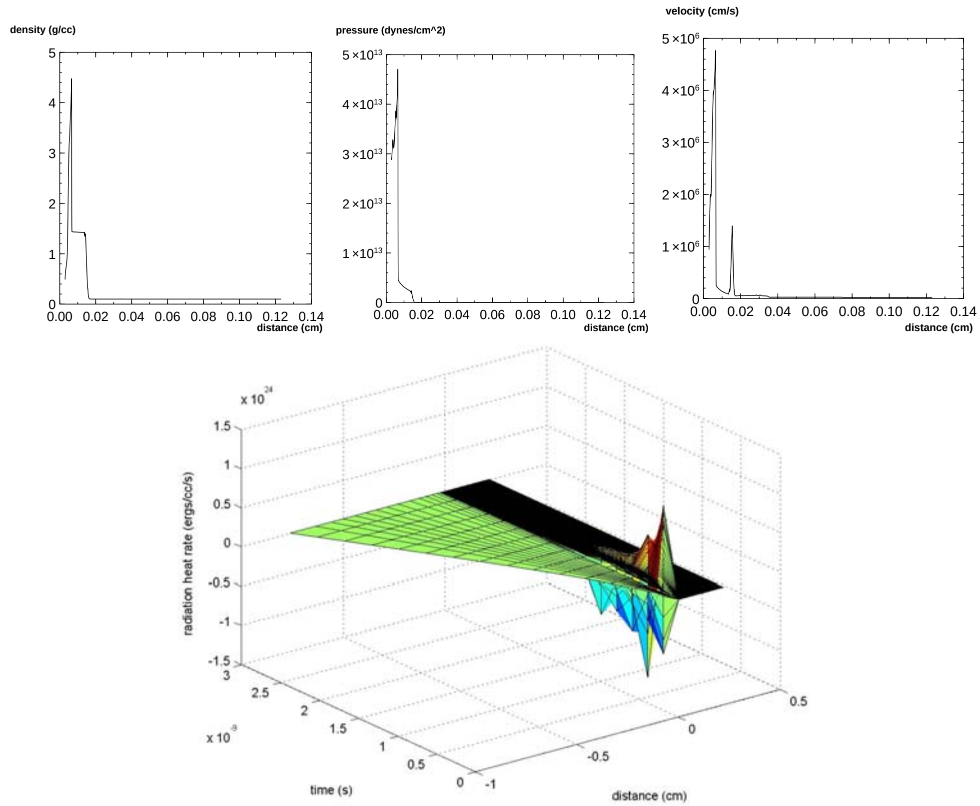

Fig. 4. *The images in the first row are the HYADES output at 1 ns as initial condition for FronTier for the high radiation case. The image in the second row is the space-time dependent radiation heat rate from HYADES as energy source for FronTier.*

contact interface is located at 150 μm. We ran the FronTier simulation with the input data displayed in Fig. 2 from 1 ns to 2 ns. The profiles for density, pressure, and velocity are shown for 1 ns, 1.5 ns, and 2 ns for both FronTier and HYADES results in Fig. 3, which demonstrates an excellent agreement between two codes.

4 High Radiation Heat

In this case the HYADES calculations were done with a different target that would produce much higher levels of radiation preheat. The entire layer of dense material is now brominated plastic (150 μm thick, $\rho = 1.42\ g/cm^3$). The interaction of the laser with this material produces much higher levels of radiation preheat. Such an experiment could be done. In addition, however, these conditions may model the preheat by energetic electrons that might be present in actual experiments, even using only low-Z materials such as polyimide as the first layer. HYADES output at time 1 ns are shown in Fig. 4 from which we see that heat rate has spread over more space and is higher in

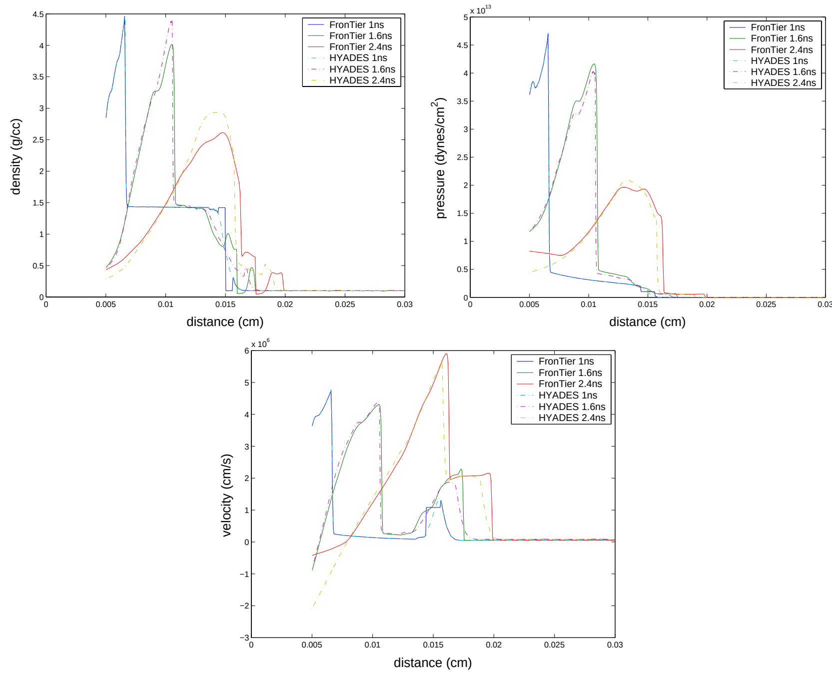

Fig. 5. *Comparison of FronTier and HYADES at 1 ns , 1.6 ns, and 2.4 ns for the high radiation case.*

magnitude than in the case in the previous section. The FronTier simulation is conducted from time 1 ns to 2.4 ns with the input from Fig. 4. Fig. 5 shows the comparison for density, pressure, and velocity for times 1 ns, 1.6 ns, and 2.4 ns for both codes. Again the agreement between FronTier and HYADES is obtained. However in this case, we find the interface has moved by 25 μm at 2.4 ns when the shock is yet to reach the interface whereas such preheat motion is not significant in the low radiation heat case. From the density and velocity plots we also see that the material ahead of interface has been perturbed at time 2.4 ns and has positive velocity.

Our 2d FronTier simulation is carried out for a 1200 μm long axisymmetric tube with a radius of 400 μm in the (r, z) domain in cylindrical geometry. The initial contact interface is perturbed by 8 sine waves with peak-valley amplitude of 5 μm at the height of 150 μm. In order to set up the initial data for the 2d run, we perturb the 1d data of Fig. 4 in six equal r-spaced vertical z directions with interface positions shifted along sine wave. Then these data are mirror reflected to generate the data on the full sine wave, which in turn are replicated to the interface of eight sine waves and the whole domain so that states at any point can be obtained by interpolation. The interface was initially perturbed by eight sine waves with peak-valley amplitude of 5 μm and driven by a upward shock. The interface evolution for our front tracking simulation is shown in Fig. 6 for time 1 ns, 1.6 ns, 2.4 ns, 6 ns, and 10 ns. Fig. 6 again demonstrates that the interface has moved by an amount similar to the corresponding 1d simulation when the shock is about to reach interface

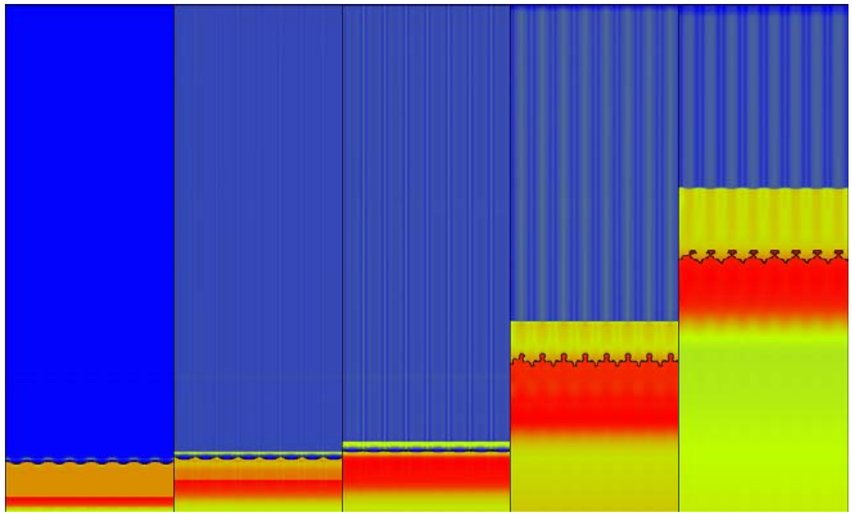

Fig. 6. *Density plots for a cylindrical simulation at 1 ns, 1.6 ns, 2.4 ns, 6 ns, and 10 ns. The interface is initially perturbed by eight sine waves with peak-valley amplitude of 5 μm and driven by a upward shock. The left boundary is the rotational axis.*

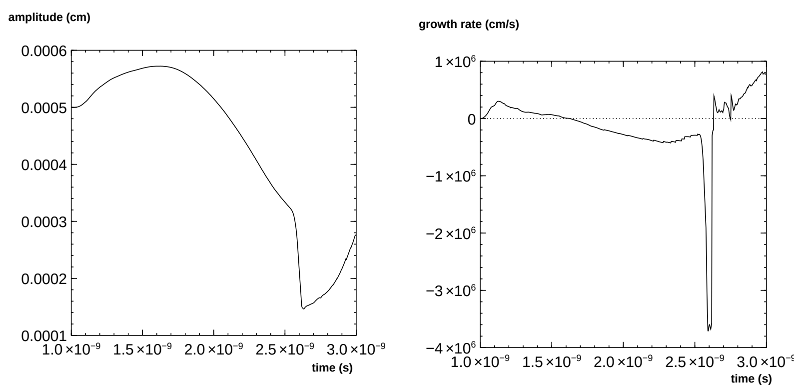

Fig. 7. *The amplitude and growth rate of the interface perturbation.*

at 2.4 ns. But what is more interesting is that the shape of perturbation is changed before the shock reaches the interface. We see the interface is flattened at 2.4 ns. In addition, by this time velocity perturbations exist along the interface, so that the initial conditions seen by the shock include perturbations in both density and velocity. The amplitude and growth rate of the perturbation are plotted as functions of time in Fig. 7, where we observe that amplitude increases slightly from 5 μm to 5.6 μm between 1 ns to 1.6 ns, then decreases significantly from 1.7 ns to 2.5 ns when the shock has almost hit the interface. Mushroom type interface shapes which are characteristics of Richtmyer-Meshkov instability are demonstrated at later times 6 ns and 10 ns in Fig 6.

5 Conclusions

We have presented a radiation coupled front tracking algorithm for intensive laser experiments in laboratory astrophysical system. Here we have proposed a pipeline method for inter-package coupling where the radhydro output is piped to the hydrodynamic input. The radiation heat rate from HYADES for the period of radiation transfer is converted to an energy source in space-time zones for FronTier, where interpolation is used to map the data in a Lagrangian moving mesh to the data in Eulerian fixed grid.

Our simulations are carried out for both low and high radiation heat rates in one and two dimensional cases. Our results are validated by comparing the FronTier output to the data produced by HYADES in the one dimensional case. We have observed significant preheat interface motion due to radiation process. We also find the shape of the interface perturbation can be altered enormously by the radiation preheat. This motivates direct experimental measurements of preheat as part of any complete study of shock-driven instabilities by such experimental methods.

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